Basics of UV Fluorescence

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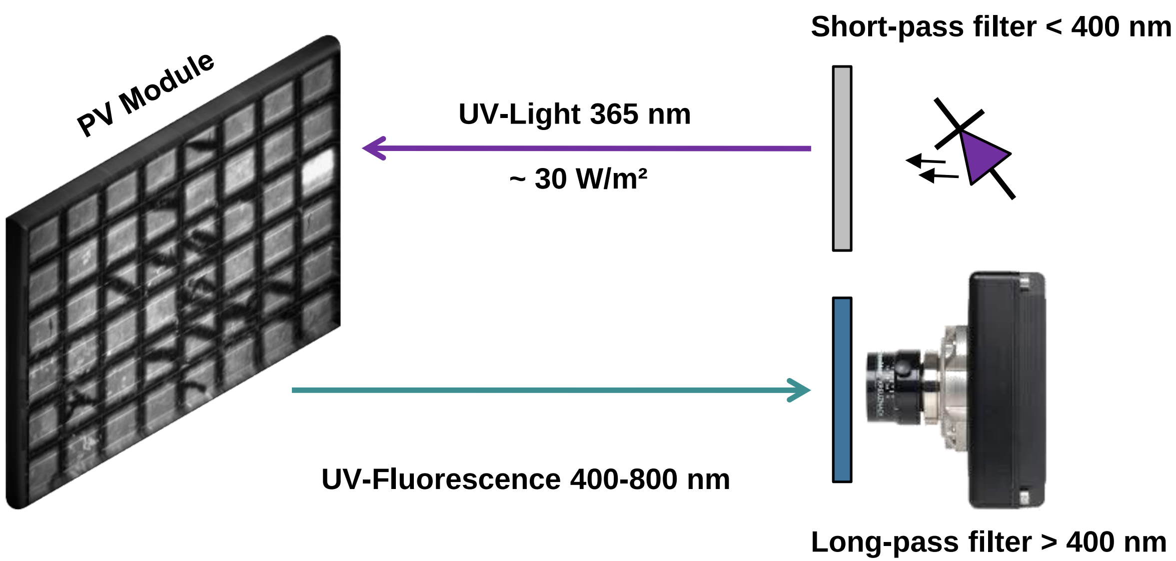
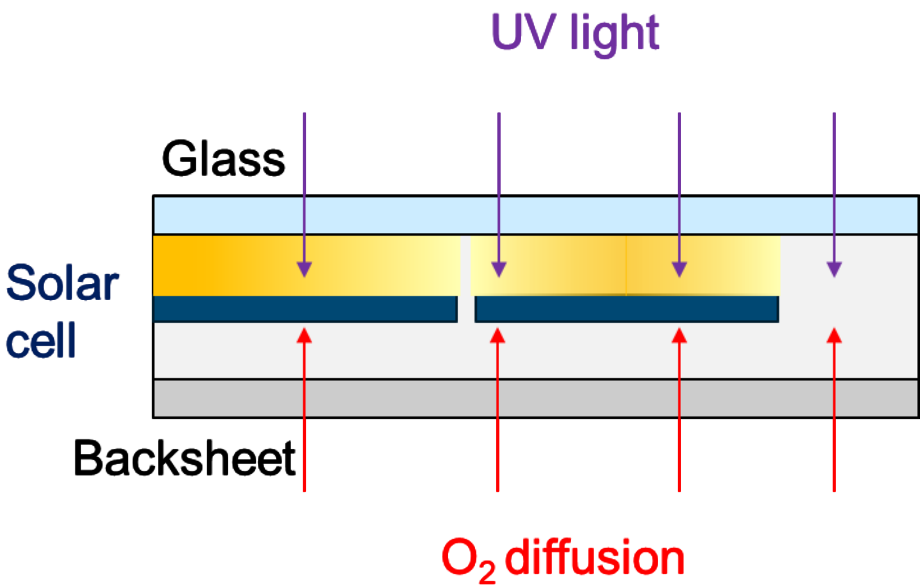
Fluorescence (FL) imaging principle



- Signal is generated by the fluorophores excited by UV light
- Module is not disconnected from circuit

M. Köntges, S. Kajari-Schröder, I. Kunze, *IEEE Journal of Photovoltaics*, vol. 3, pp. 95-101, 2013.
A. Morlier, M. Siebert, I. Kunze, M. Köntges, G. Mathiak, *IEEE Journal of Photovoltaics*, vol. 7, pp. 1710-1716, 2017.

Principle of UV fluorescence

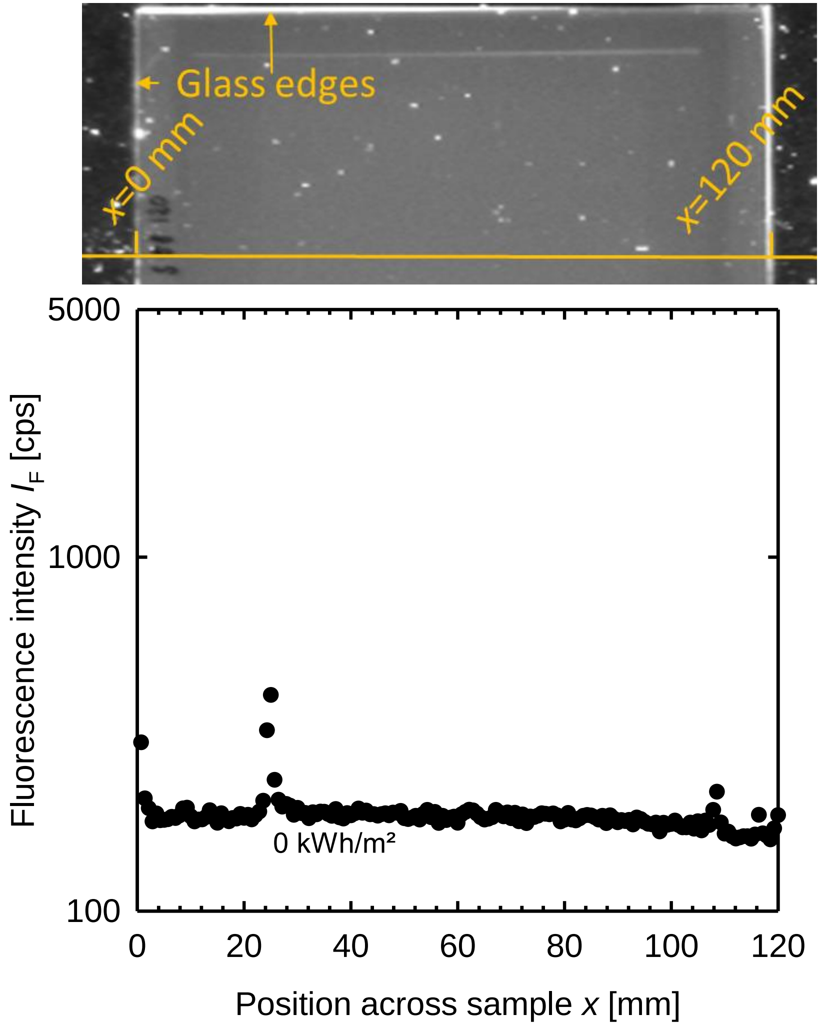


- Fluorescent degradation products are formed under sun exposure
- UV absorbers may be the precursors of fluorophores
- Oxygen + light bleach the fluorophores
- Oxygen diffusion through cell cracks and at cell edges

→ Extinction of UV fluorescence in their vicinity

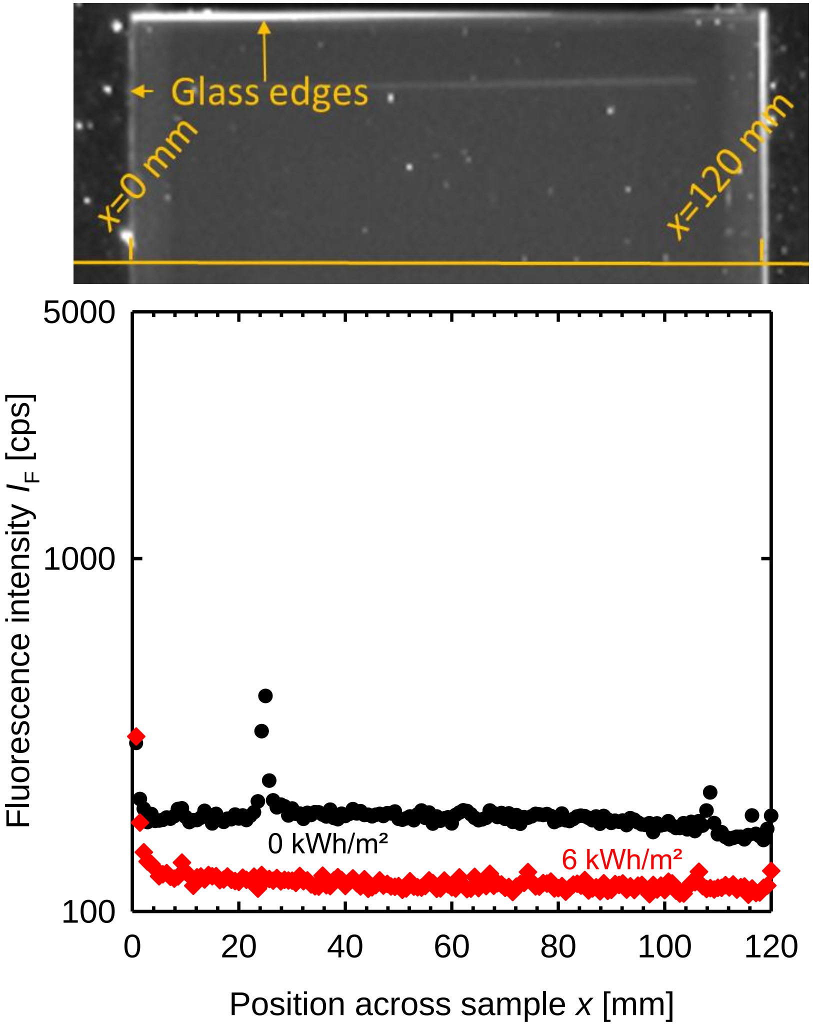
Basic literature on fluorescence:
[1] F.J. Pern, *Solar Energy Materials and Solar Cells,* 41/42, 1996, pp. 587-615
[2] L. King, M.A. Quintana, J.A. Kratochvil, D.E. Ellibee, B.R. Hansen, *Progress in Photovoltaics: Research and Applications*, vol. 8, pp. 241–256, 2000.
[3] J. Schlothauer, S. Jungwirth, M. Köhl, B. Röder, *Solar Energy Materials and Solar Cells*, vol. 102, pp. 75-85, 2012

Fluorescence pattern over time



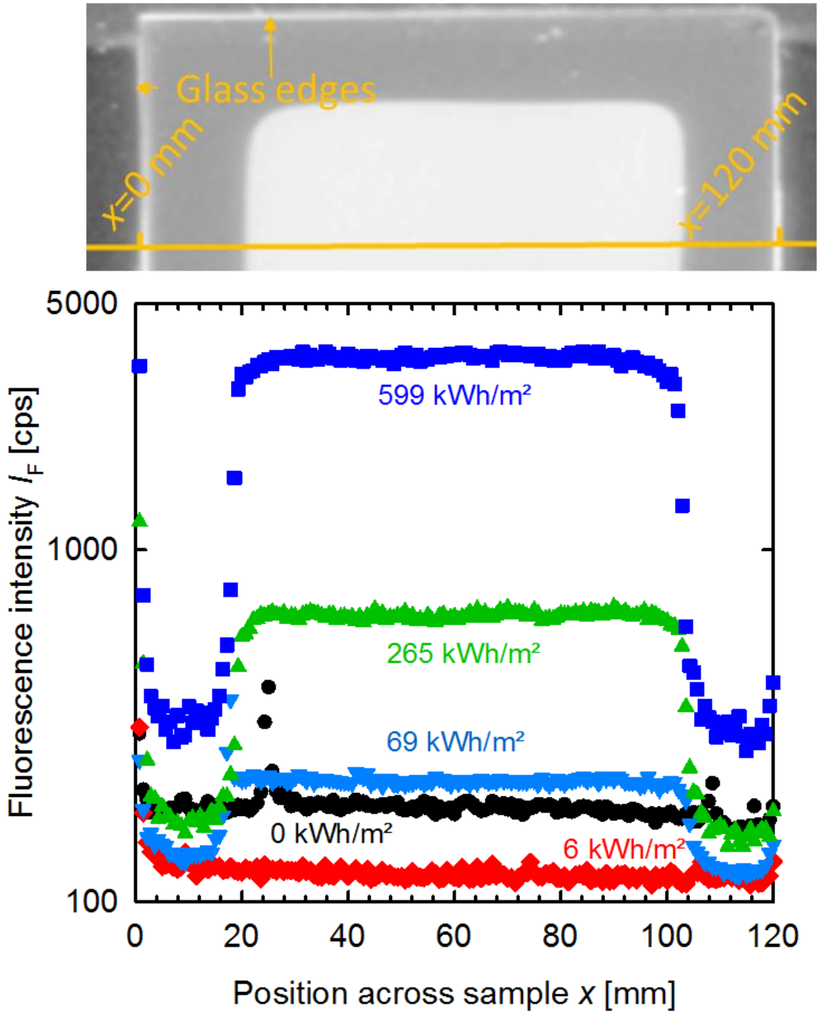
- Glass/EVA/Glass laminate under ca. 280 W/m² UV
- Initial: homogeneous fluorescence

Fluorescence pattern over time



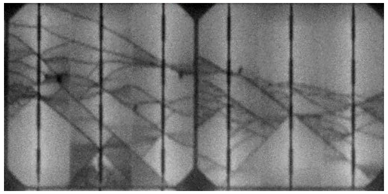
- Glass/EVA/Glass laminate under ca. 280 W/m² UV
- Initial: homogeneous fluorescence
- Extinction of fluorescence within first kWh/m²

Fluorescence pattern over time



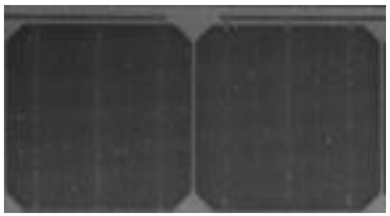
- Glass/EVA/Glass laminate under ca. 280 W/m² UV
- Initial: homogeneous fluorescence
- Extinction of fluorescence within first kWh/m²
- Increase of I_F in the central area x = [30, 90] mm
- Edges with lower fluorescence intensity
- Homogeneous central area

Fluorescence along initial cracks

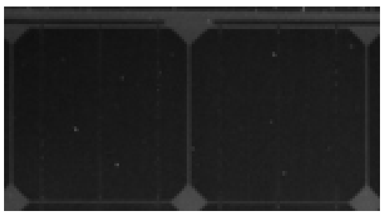


Initial EL image

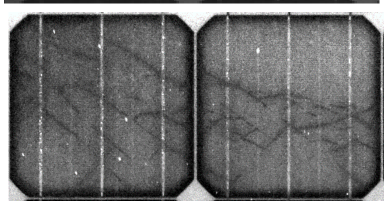
UV Fluorescence images



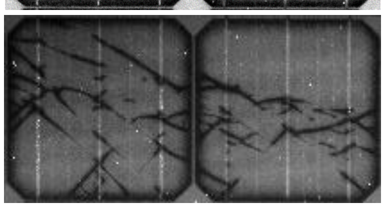
Dose: 0 kWh/m²
Day 0



Dose: 4 kWh/m²
Day 1



Dose: 117 kWh/m²
Day 21



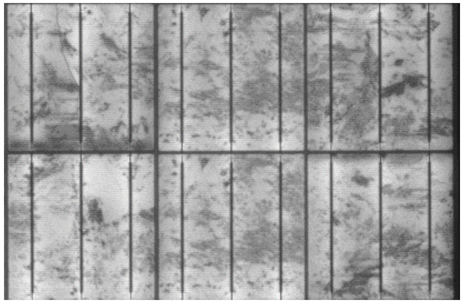
Dose: 398 kWh/m²
Day 77

- Mono-Si Module, never exposed to sunlight
- 2 cells with cracks
- Initial: homogeneous fluorescence over the whole surface of the module[1,2]
- Subsequently: Outdoor exposure, short circuited
- After 3 weeks in summer the initial cracks are visible with UVFL

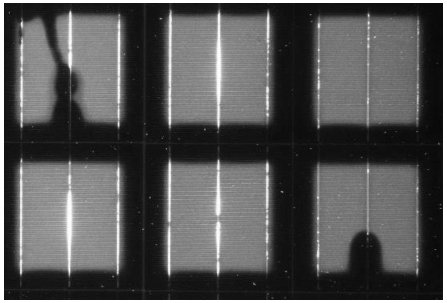
[1]A. Morlier, M. Köntges, S. Blankemeyer, I. Kunze, *Energy Procedia*, vol. 55, pp. 348-355, 2014.
[2]J. Schlothauer, M. Ralaiarisoa, A. Morlier, M. Köntges, B. Röder, *Journal of Polymer Research*, vol. 21, pp.457-463, 2014.

Apparition of new cracks

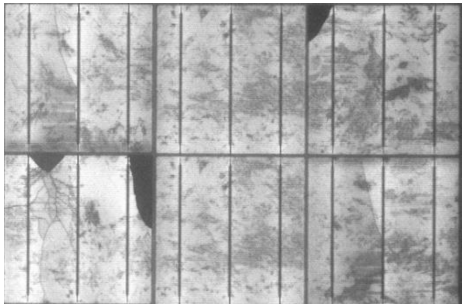
Electroluminescence



Fluorescence



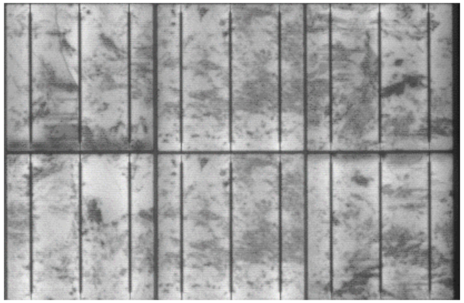
- Multi-Si module
- 4 years on a carport
- 2 cells show cracks with a complete bleaching of the fluorescence
- Cracks best seen with FL



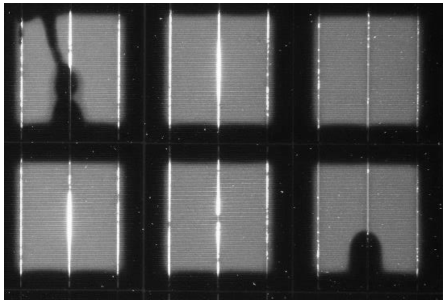
2 cells are intentionally broken, subsequent installation on a roof.

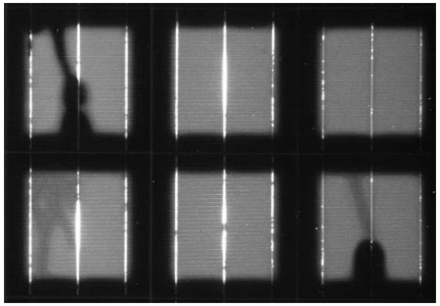
Apparition of new cracks

Electroluminescence

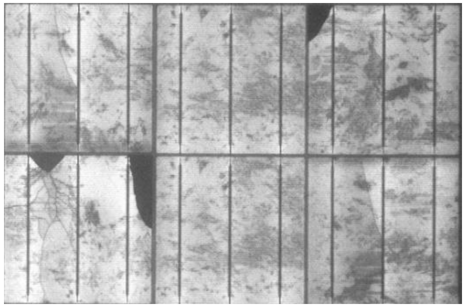


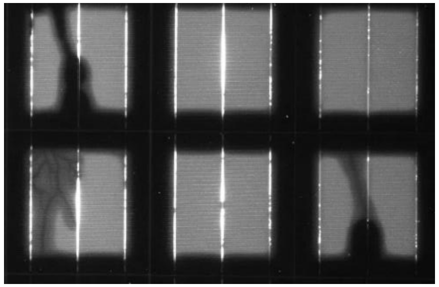
Fluorescence





6 Days Outdoor
(5 kWh/m²)

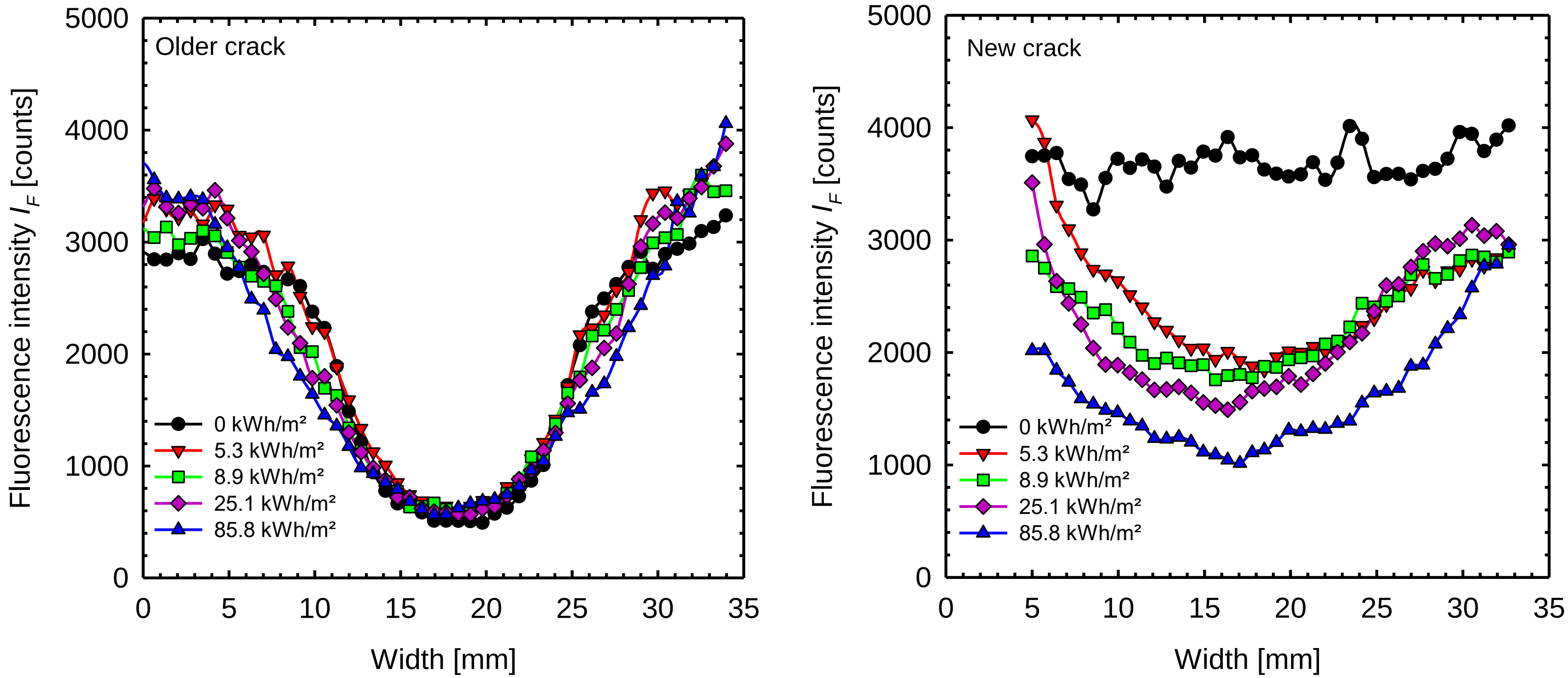




70 Days Outdoor
(86 kWh/m²)

- Multi-Si module
- 4 years on a carport
- 2 cells show cracks with a complete bleaching of the fluorescence
- Cracks best seen with FL
- 6 days: partial bleaching at new cracks
- 10 weeks: still possible to discern new cracks from old ones

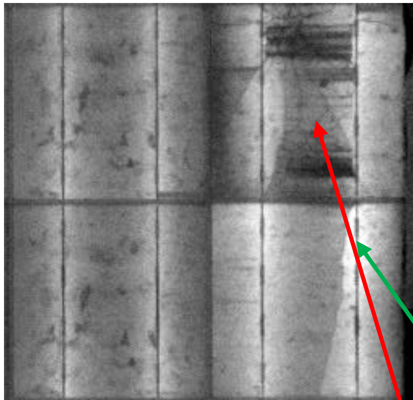
FL decrease along cracks



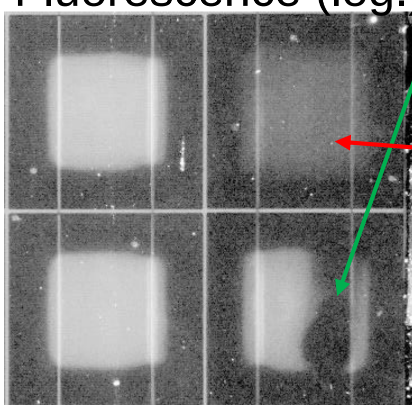
- Old crack, cell edge: no change in FL
- New crack: FL decrease already after 5.3 kWh/m², but FL intensity after 10 weeks > FL on old crack

Application: hail storm damage

Electroluminescence



Fluorescence (log.)

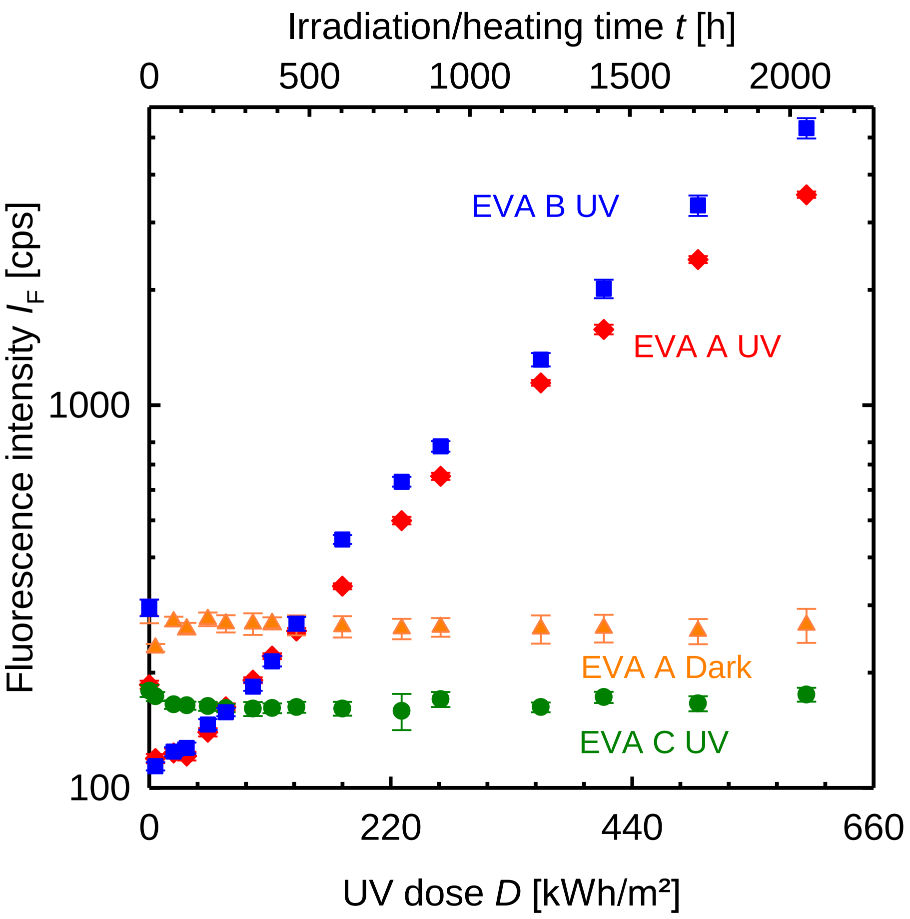


Old crack with full extinction, comparable to oxygen diffusion at cell edge

New cracks, partial extinction

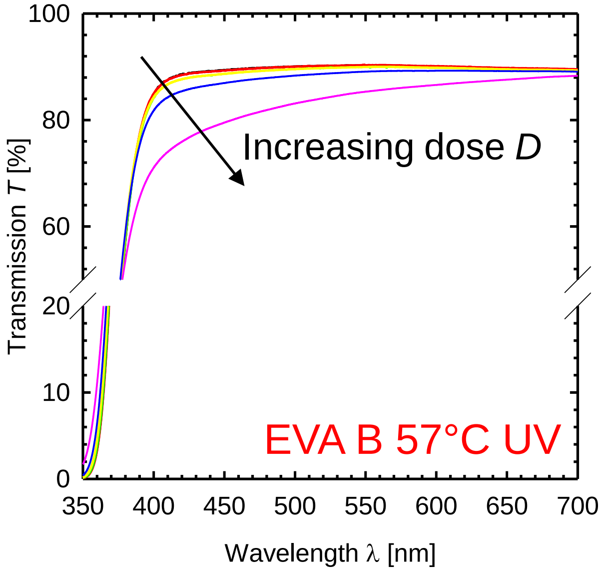
- Old cracks (e.g. caused during installation) and cell edges appear black (full extinction)
- Recent cracks: local partial extinction of FL
- 8 weeks after the storm, difference is still visible
- Fluorescence discriminates old cracks from new ones

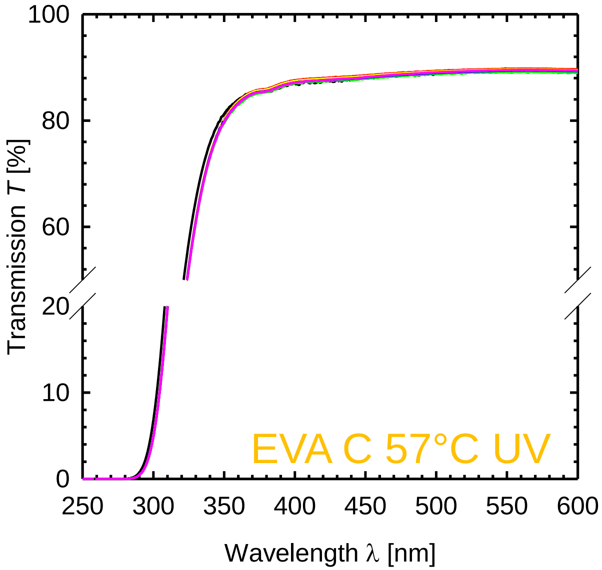
I_F vs. UV dose



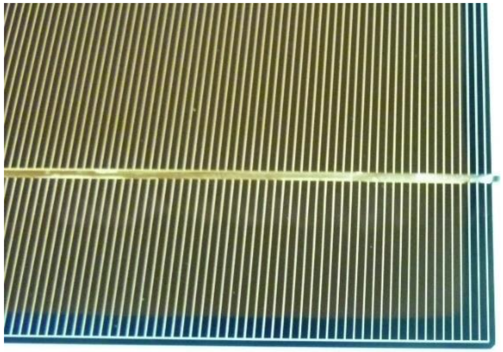
- Glass/EVA/Glass laminate under ca. 280 W/m² UV @ 57°C
- Three EVAs (A, B, C)
- EVA C has a shorter cut-off wavelength (330 nm)
- EVA kept in the dark at 57°C: no fluorophores
- UV „transparent“ EVA (C): no fluorophores

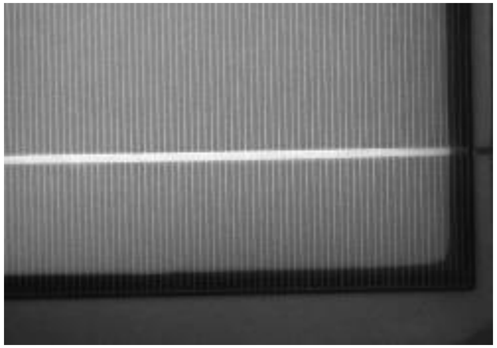
Spectral changes in EVA



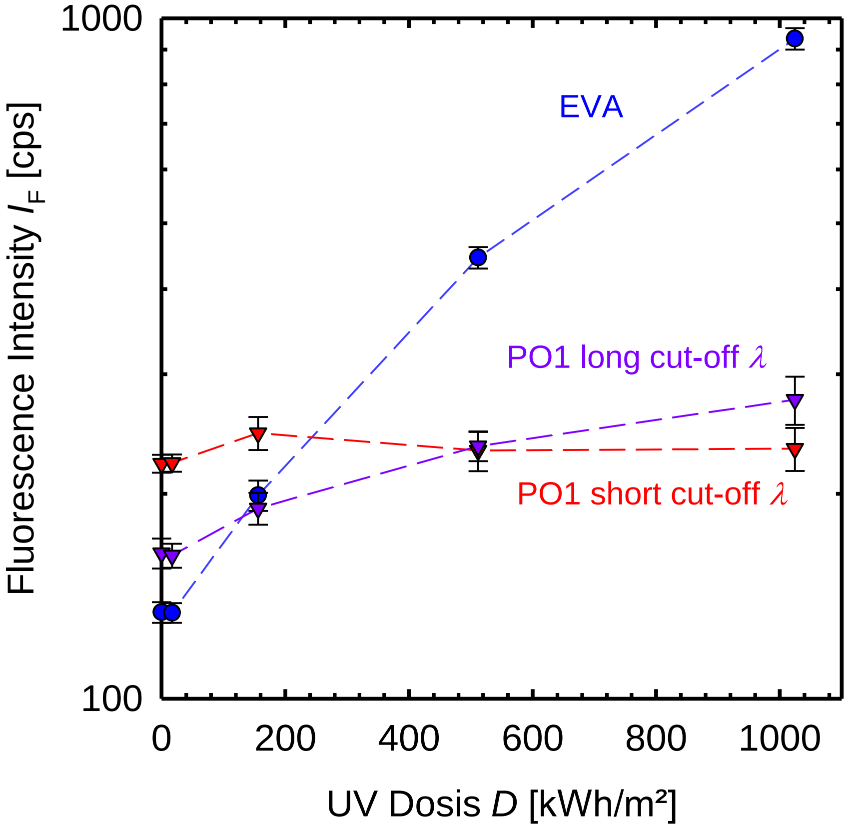


- For EVA A and B, transmission *T* decreases with increasing dose *D*
- EVA without UV absorber (C): no notable change



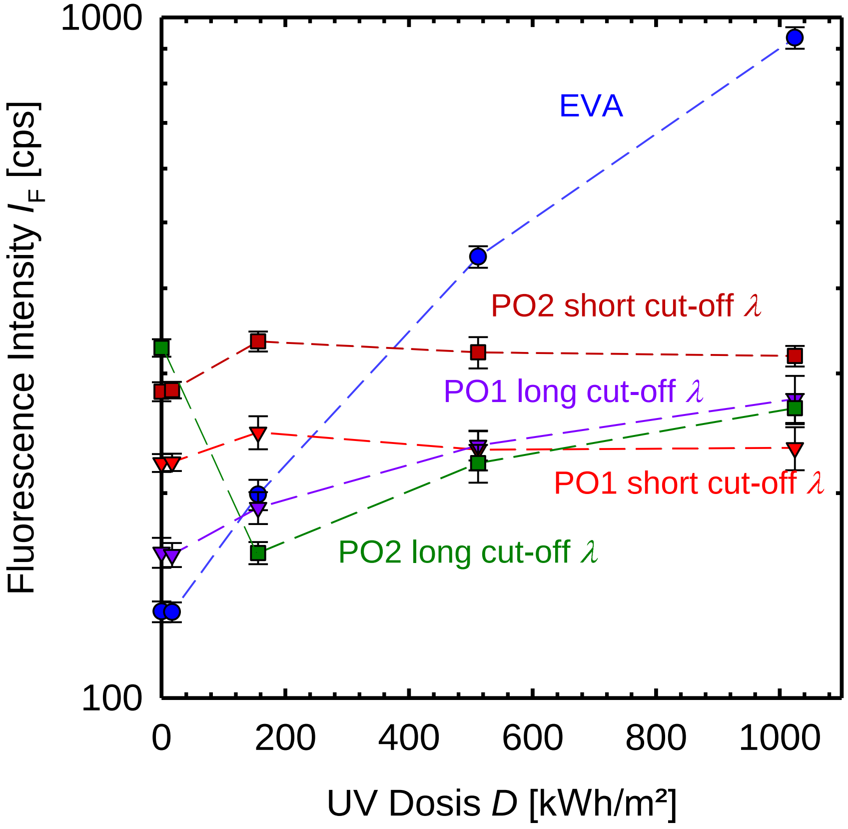


Polyolefins



- Comparison EVA (prev. EVA A) with polyolefins (PO)
- POs with different UV absorbers
- Fluorophore formation observed in every material
- PO with lower cut-off: less fluorophore formation

Polyolefins



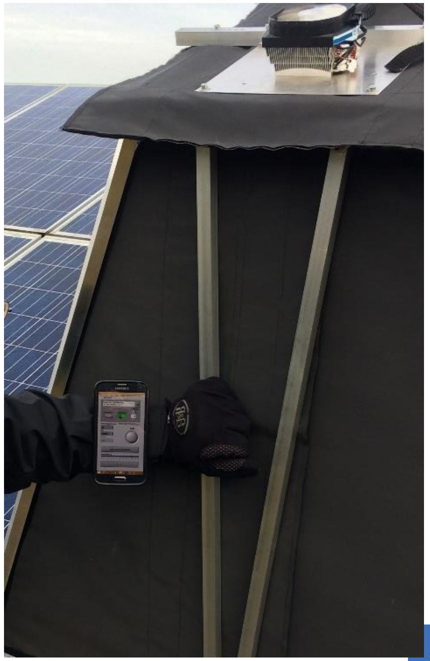
- Comparison EVA (prev. EVA A) with polyolefins (PO)
- POs with different UV absorbers
- Fluorophore formation observed in every material
- PO with lower cut-off: less fluorophore formation
- Same is observed with PO from another manufacturer

FL Outdoor Inspection System

- Transportable in a car trunk

- 0.5 h mounting
- Adaptable to module size
- No electrical connection of the modules

- Single operator
- Controlled via a smartphone
- 4 h autonomy/battery
- Up to 200 modules/h
- Measurement under sunlight



Conclusion

- Fluorescent degradation products are formed under sun exposure
- Oxygen + light bleach the fluorophores
- Initial cracks revealed after 3 weeks exposure
- New cracks detectable after 1 week exposure
- Newer cracks distinguishable over 3 months
- Fluorescence correlates with yellowing
- Materials with shorter cut-off form less fluorophores (or not at all)
- The same is valid for polyolefin materials
- Fast detection method in the field or in the lab

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